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The quest for a better solvent for the direct hydration of cyclohexene: From molecular screening to process design



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HIGHLIGHTS

- Multiscale method for selection of eco-efficient solvents for cyclohexene hydration.
- Acetophenone as effective solvent that reduces costs by 7.8 % and CO₂ emissions by 16.9 %.
- New solvent doubles the yield, without side reactions and catalyst deactivation.

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ABSTRACT

Cyclohexanol is an essential bulk chemical that can be produced via cyclohexene hydration, a liquid-liquid two-phase reaction that is limited by the low reaction rate and the equilibrium conversion. Adding an appropriate solvent is the most promising method to break through these limitations. However, in previous works the solvent was almost blindly selected without a global consideration. In this work, a rational multiscale method is proposed for the effective selection of an economical and sustainable solvent for the direct hydration of cyclohexene. At the molecular scale, liquid-liquid phase equilibrium was estimated using group contribution methods to rapidly screen the potential solvent candidates from a range of organics, based on the partition coefficient. At the reactor scale, the candidates were experimentally investigated to pick out the solvents that could significantly improve the conversion, without introducing side reactions or deactivating the catalyst. At the process scale, the total annual cost (TAC), CO₂ emission, and other metrics were calculated to evaluate the eco-efficiency of all solvents. Using this multi-scale method, acetophenone was selected as an eco-efficient solvent from over 100 organics, resulting in the reduction of TAC by 8 % and CO₂ emission by 17 % in the production process. Using acetophenone also led to the increase of cyclohexanol yield from 12.3 % to 27.6 % without the occurrence of side reactions and catalyst deactivation.

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1. Introduction

As an important feedstock in the polymer industry, cyclohexanol has a very large demand so its high-efficiency production has received much attention (Long et al., 2015; Mokaya and Poliakov, 2005; Sarak et al., 2021; Sommer et al., 2018). Overall, there are three established industrial routes to produce cyclohexanol, including phenol hydrogenation (Liu et al., 2009; Liu et al., 2022a, 2022b), cyclohexane oxidation (Contreras et al., 2019) and cyclohexene hydration (Ishida, 1997). Compared to other routes, the direct cyclohexene hydration (which is a typical liquid-liquid two-phase reaction catalyzed by the zeolite HZSM-5) has the

advantages of high atom economy and low safety hazards, thus gradually becoming a high-profile enhanced cyclohexanol production method (Imam et al., 2013; Katariya et al., 2009; Kurnar et al., 2011; Steyer et al., 2008; Zhu et al., 2021).

In the direct hydration of cyclohexene to produce cyclohexanol there are two limiting factors: 1) extremely low solubility of cyclohexene in the aqueous phase (Frolkova et al., 2018; Steyer and Sundmacher, 2004), where the catalyst is suspended and the reaction occurs, leading to low hydration rate and large reactor volume (Zhang et al., 2002); and 2) low equilibrium conversion of cyclohexene, less than 12 % (Shan et al., 2011a, 2011b), which means that additional equipment and larger operation costs are needed to recover the unreacted cyclohexene. In general, three solutions have been applied to break through these limitations, including the preparation of highly active catalyst (Liu et al., 2021; Meng

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Nomenclature

$C\%$	Carbon content	TAC	Total annual cost, \$/year
CSTR	Continuous stirred tank reactor	TOC	Total annual operation cost, \$/year
c_{ene}	Cyclohexene concentration in aqueous phase, mol/L	TEC	Total equipment cost, \$/year
c_w	Water concentration in aqueous phase, mol/L	NHV	Net heating value
c_{nol}	Cyclohexanol concentration, mol/L	N_p	Power number
E_{CO_2}	CO ₂ emission, kg/h	m	Partition coefficient
h_{seq}	Enthalpy of the required steam, kJ/kg	MCW	Molar ratio of cyclohexene to water
Q_{fuel}	Fuel consumption	MSC	Molar ratio of solvent to cyclohexene
Q_{seq}	Energy consumption of the process, kJ/kg	Y	Yield of cyclohexanol
R	Ideal gas constant, 8.314 J/(mol·K)	α	Ratio of molecular weight between carbon dioxide molecule and carbon atom
t	Reaction time, min	λ_{seq}	Latent heat of the required stream, kJ/kg
T	Reaction temperature, K		
T_F	Flame temperature, K		
T_S	Stack temperature, K		
T_0	Ambient temperature, K		

et al., 2016; Ogawa et al., 1998), use of reactive distillation (RD) (Chen et al., 2014; Hu and Tian, 2021; Khaledi and Bishnoi, 2006; Liu et al., 2022a, 2022b; Qi et al., 2002, 2013; Steyer et al., 2002; Taipabu et al., 2021; Wang et al., 2020a, 2020b; Ye et al., 2011, 2014; Yu et al., 2016; Zheng et al., 2017) and the addition of an appropriate solvent (Panneman and Beenackers, 1992a). At present, selecting an effective solvent is the most promising direction for industrial implementation.

Adding solvents to the system intensifies the cyclohexene hydration by increasing the cyclohexene concentration in the aqueous phase, resulting not only in the acceleration of reaction but also the shift of the chemical equilibrium towards cyclohexanol formation (Frolkova et al., 2016; Qiu et al., 2012). Several solvents were used so far, such as sulfolane (Panneman and Beenackers, 1992b,c,d), ethylene glycol (Shan et al., 2011a, 2011b), and dioxane (Qiu et al., 2013). An increase of the equilibrium yield could only be reached at a very high solvent-cyclohexene molar ratio, but the large amount of solvent required would lead to an energy intensive recovery of it. Additionally, in previous works the solvents were selected without a global consideration. However, an economical and sustainable solvent for the cyclohexene hydration should meet the following requirements: 1) it must greatly improve the cyclohexanol yield and reaction rate; 2) it must be an inert (not allowed to react with any reactants and/or products); 3) it will not shorten the service life of the catalyst used; and 4) it forms no azeotropes with the reactants and products in order to avoid larger separation cost. Therefore, selecting a suitable solvent for the cyclohexene hydration is a complex task, inviting our consideration of every scale. This key research gap is covered in this present work.

A similar challenge, which has been encountered in the screening of dilution and separation solvents, was tentatively solved by developing a multi-scale method (Chai et al., 2022; Cheng et al., 2022; Gertig et al., 2020; Lei et al., 2021; Papadakis et al., 2016; Song et al., 2018; Tobiszewski et al., 2015; Wang et al., 2020a, 2020b; Zhang et al., 2020; Zhou et al., 2020). Although this method was successful in the selection of extractants (mass separating agents) (Sun et al., 2019), it has not been widely used in the screening of solvents for reaction systems. The main difficulty is that different multi-scale strategies should be tailored for the selection of different reaction solvents, due to the complexity of the reaction systems (Zhou et al., 2015). The particularity of the solvent for the reaction of liquid-liquid heterogeneous cyclohexene hydration is that it plays the role of both reaction and separation solvent in the reaction system. This dual role requires skillful setting of the evaluation indicators at different scales to simultaneously ensure

accuracy and efficiency. With the establishment of such a multi-scale method, a suitable solvent could be efficiently and accurately selected from the massive amount of organic chemicals, to reduce the total cost and improve the sustainability of the cyclohexanol production by the direction hydration of cyclohexene.

This novel work develops a multi-scale method to select suitable solvents for the cyclohexene hydration reaction, as illustrated in Fig. 1. At the molecular scale, the liquid-liquid phase equilibrium (LLE) is calculated for different solvents to quickly narrow the selection range of the solvent by using a novel evaluation parameter, which remarkably reduces the subsequent workload. Then, the selected solvents are experimentally evaluated at the reactor scale by the reactant conversion, product selectivity, and catalyst performance repeatability. This step is used to further reduce the selection range of the solvent, and to investigate the actual effects brought by the solvent selected. Finally, taking the whole technological process into account, an economic and sustainable analysis is conducted at system scale using rigorous simulations in Aspen Plus for a reduced number of selected solvents.

2. Experimental materials and methods

Cyclohexene and cyclohexanol were commercially supplied by the Shanghai Aladdin Biochemical Technology Co., Ltd. with purity greater than 99.6 wt% and 99.0 wt%, respectively. More than 60 solvents were experimentally investigated in this work. Their CAS numbers, purities and suppliers are listed in Table S1 in the Supporting Information. The molecular sieve zeolite catalyst H-ZSM-5 (SiO₂/Al₂O₃ = 25) was provided by the Nankai University catalyst Co., Ltd. It was calcined at 773 K for 4 h and stored in desiccators for future use.

The hydration reaction was performed in a 500 mL stainless steel batch tank reactor equipped with agitation and temperature control devices (see Figure S1 in the Supporting Information). The stirrer is a mechanical stirring paddle controlled by an electric machine. In each run, a specified amount of catalyst, cyclohexene, water, and solvent was first charged into the reactor. After being sealed up, the reactor was filled with nitrogen to the pressure of 1.0 MPa to avoid the vaporization of the reactant liquid under the reaction temperature. A slow stirring speed of 100 rpm was set during the heating process to promote a uniform temperature distribution in the reactor. As the mixture was heated to the reaction temperature required, the agitation speed was raised to the desired level. This moment was regarded as the initial time. The stirring was stopped after a fixed reaction time, and the reactor was cooled to 50 °C. Then, the solid catalyst was separated from

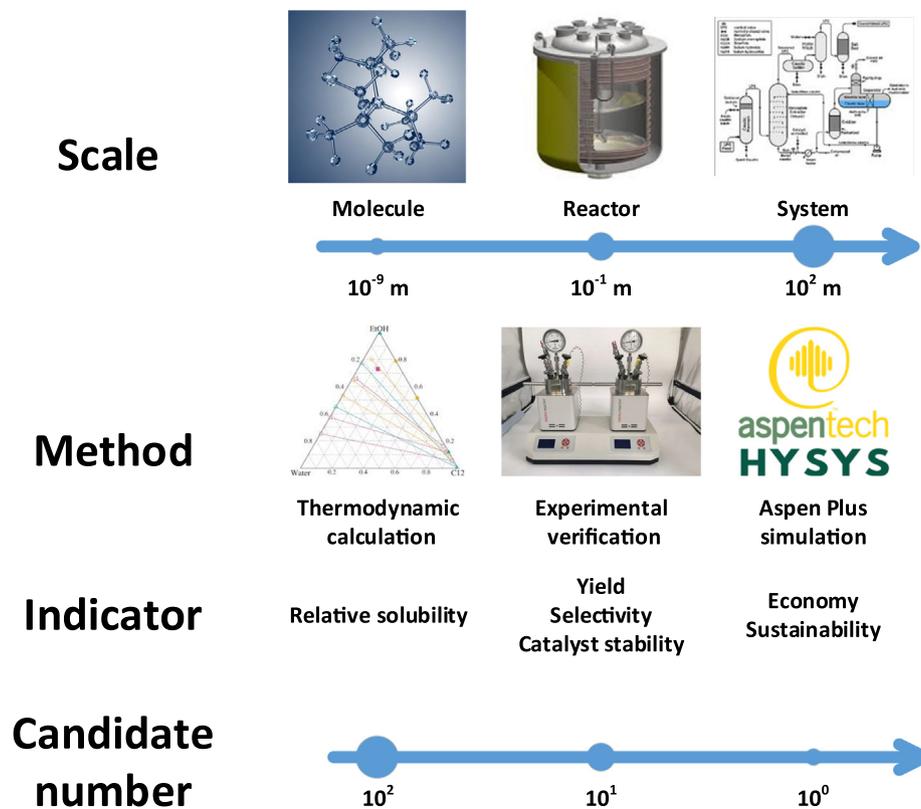


Fig. 1. Research framework of this work.

the mixture by a piece of filter cloth, and the liquid was poured into a separating funnel for the liquid–liquid phase split. The cyclohexene and cyclohexanol in the aqueous phase were extracted using ethyl acetate. The extraction phase was mixed with the organic phase for the quantitative analysis by gas chromatography.

A validated Othmer kettle was used to conduct the vapor–liquid equilibrium (VLE) experiment (see Figure S2 in the Supporting Information). The Othmer kettle provided vapor–liquid double-cycle equilibrium with a fast displacement function. A vacuum insulation jacket was installed on outside of it to reduce the heat loss. The liquid phase in the boiling chamber was heated to vaporize by a heating rod connected to an adjustable transformer. The vapor was condensed in the condensation tube. The condensed fluid returned into the boiling chamber successively through the sampling outlet and reflux tube. Observing the boiling condition continuously, it was considered that liquid phase begins to boil when a large number of bubbles appeared at the liquid surface, then the thermometer indication intervals of a certain time are noted. It was considered stable when the thermometer indication remained unchanged for 60 min, indicating that the vapor–liquid two phases of the system had reached phase equilibrium. The glass sampling needle was used to take samples from vapor and liquid sample connection respectively then analyzed by gas chromatography (GC). The temperature was measured using a calibrated Titr-etete precise thermometer with a standard error range of ± 0.01 K. Pressure was controlled at 101.3 kPa by an adjustable transformer (TDGC2-1, Chint Electric Co., Ltd.) with an uncertainty of 0.2 kPa.

The concentrations of cyclohexene and cyclohexanol were determined by GC (GC-2014C, Shimadzu, Japan) equipped with a flame ionization detector (FID) and a 60 m long capillary column (SH-I-1MS, Shimadzu, Japan), using methylbenzene as a standard substance. The temperature profile was programmed as follows: start at 313 K and hold for 1 min, then increase to 356 K at 20 K/

min and hold for 1.5 min, then increase to 433 K at 40 K/min and hold for 1 min, then increase to 553 K at 40 K/min and hold for 2 min. The temperatures of the injector and detector were both set as 573 K. High-purity nitrogen was used as carrier gas at 0.7 MPa.

2.1. Simulation and evaluation methods

In order to evaluate the solvent effect at molecule scale, LLE calculation was conducted in Aspen Plus using the NRTL (non-random two-liquid) property model. The model parameters were extracted from Aspen Plus for the ternary system of cyclohexene–water–cyclohexanol (listed in Table S2). These parameters were verified by the experimental data, and widely applied in the simulation of cyclohexene hydration processes (Chen et al., 2014; Liu et al., 2022a, 2022b; Taipabu et al., 2021). Figure S3 compares the experimental liquid–liquid data provided by Steyer and Sundmacher (2004) with those predicted by the NRTL model. The small deviation indicates that it is adequate to use the NRTL model and the parameters in Table S2 for the liquid–liquid phase equilibrium calculation. After the solvents are added, more parameters of the NRTL model are required. Considering that more than 100 solvents have been investigated by simulation, it was unpractical to determine experimentally these parameters. For this reason, the missing parameters were estimated by Aspen Plus using the UNIFAC method, which has been widely and successfully used in the prediction of thermodynamic properties (Bacicheti et al., 2021; Brandolín et al., 2022; Machado et al., 2019; Yalın et al., 2020).

At the system scale, the technological process, which mainly included reactor, heat exchanger and distillation column, was simulated by Aspen Plus. Reactor was simulated using the model of RYield, which requires the dependence of yield on reaction conditions. In this work, the yield of cyclohexanol were determined at

various conditions for different solvents to establish this dependence. Heat exchangers were simulated using the HeatX model. The distillation columns were simulated using the RadFrac model. The reflux ratio and number of theoretical plates were estimated based on the shortcut model DSTWU, under the given design specifications. The dividing-wall column (DWC) was simulated using its thermodynamically equivalent scheme. Accurate thermodynamic parameters are very important for rigorous process simulation. Here, the NRTL model was used to describe the VLE. Some of the interaction parameters of this model are not in the database of Aspen Plus. They are correlated with the VLE data predicted with the UNIFAC model. These predicted VLE data was further verified experimentally. Once the predicted deviated much from the experimental one, the relevant interaction parameters were correlated with the experimental data in Aspen Plus by its function of data regression.

The total annual cost (TAC) was calculated for the economic evaluation of the processes. It includes both the equipment and operating costs (Douglas, 1988):

$$TAC = \frac{TEC}{n} + TOC \quad (1)$$

TEC and TOC represent the total equipment cost and total operational cost, respectively, while n is the payback period (years) assumed to be 3 years with 8000 h/year (Dimian et al., 2014; Luyben, 2012). TEC contains the cost of reactor, heat exchanger, decanter, and distillation column. The cost of the auxiliary equipment, such as pump and pipeline, was generally neglected due to the much lower price comparatively. TOC mainly included the cost of cooling water and heating utility (steam). The detailed calculation equations for TEC and TOC are listed in Table S11 and S12 in the Supporting Information, respectively.

The CO₂ emission E_{CO_2} (kg/h) was used to assess the environmental performance (Smith and Delaby, 1991):

$$E_{CO_2} = \left(\frac{Q_{fuel}}{NHV} \right) \times \left(\frac{C\%}{100} \right) \alpha \quad (2)$$

$\alpha = 3.67$ was the ratio of molecular weight between carbon dioxide molecule and carbon atom. The net heating NHV and carbon content C% were 39771 kJ/kg and 86.5, respectively. The fuel consumption (Q_{fuel}) is given by:

$$Q_{fuel} = \frac{Q_{seq}}{\lambda_{seq}} \times (h_{seq} - 419) \times \frac{T_F - T_0}{T_F - T_S} \quad (3)$$

The latent heat of the required steam is denoted as $\lambda_{seq} = 2083.47$ kJ/kg. The enthalpy of the required steam is expressed as $h_{seq} = 2683.64$ kJ/kg. The energy usage is Q_{seq} (kJ/h). The flame, stack, and ambient temperatures are abbreviated as T_F , T_S , and T_0 with values: 2073.15, 433.15, and 298.15 K, respectively.

To make a fair comparison of the processes provided, the operating conditions were optimized to minimize TAC. The optimization procedure is shown in Figure S4. Taking the optimization of the reactor temperature as an example, we conducted the following steps. First, a suitable reactor temperature range was chosen. Second, several reactor temperatures were chosen in that temperature range. Third, the whole process was simulated to calculate the TAC at all the temperature points selected. Forth, comparing TAC at all the temperature points, the temperature that corresponds to the minimum TAC was considered as the optimal temperature. Other operation parameters were optimized in a similar way.

3. Results and discussion

3.1. Solubility evaluation at the molecular scale

Cyclohexene hydration is limited not only by the extremely low solubility of cyclohexene in water, but also by the low equilibrium conversion (Frolkova et al., 2018; Zhang et al., 2002). Although the addition of solvent can improve the extremely low mutual solubility between cyclohexene and water, it is unadvisable to mix the two phases by adding solvent. The first reason is that a large amount of solvent should be used, resulting in a sharp increase of the cost for solvent recovery. The second reason is that the liquid–liquid two phase system provides an opportunity to pull the product (cyclohexanol) from the aqueous phase, where the hydration reaction occurs, into the organic phase to shift the chemical equilibrium. An ideal solvent for the improvement of cyclohexanol yield should combine the abilities to push the reactant (cyclohexene) into the aqueous phase from the organic phase to increase reaction rate and to pull the product (cyclohexanol) from the aqueous phase into the organic phase to shift the chemical equilibrium. The potential solvents are divided into two categories, depending on their solubility in water. The first category of solvents includes the ones completely miscible with water. Such solvents intensify the hydration reaction by significantly improving the cyclohexene concentration in aqueous phase. In previous works, this category of solvent was widely used (Panneman and Beenackers, 1992a, b, c, d; Qiu et al., 2013; Shan et al., 2011a, 2011b). The second category of solvents consists of those partly miscible with water. Such solvents intensify the hydration reaction by timely separating the generated product (cyclohexanol) from the aqueous phase into organic phase. No matter which type of solvent is used to strengthen the cyclohexene hydration reaction, it is aimed that the aqueous phase has high cyclohexene and low cyclohexanol concentrations. In view of this objective, the partition coefficient m is used to evaluate the solvent performance:

$$m = \frac{c_{ene}}{c_{no1}} \quad (4)$$

where c_{ene} and c_{no1} are the cyclohexene and cyclohexanol molar concentrations in the aqueous phase at the state of phase equilibrium. The higher this ratio m is, the stronger the attraction of the solvent to the cyclohexene molecules. This simple parameter can aid the rapid screening of an effective solvent to significantly improve the yield of product cyclohexanol.

The liquid–liquid equilibrium (LLE) of the quaternary system cyclohexene + water + cyclohexanol + solvent were calculated for nearly 100 solvents, which are classified into five categories: nitriles, ethers, ketones, phenols, and alcohols (listed in Table S3 to S7 in the Supporting Information). The value of m is ~ 0.0234 (much less than 1) without solvents, because the –OH group of cyclohexanol makes it easier to be dissolved into water than cyclohexene. However, the value of m may increase or decrease when adding a solvent. Given that a higher m benefits the improvement of reaction rate and equilibrium conversion, the solvents that significantly increase the value of m are the ones preferred. Fig. 2 provides an overview of the preferred solvents for each category.

However, directly selecting an organic solvent with the highest m value is unreasonable for the several reasons. Firstly, some of the solvent could react with the reactant or the product, which is not considered by the LLE calculation. Such unwanted side reaction must be avoided from an efficient atom economy perspective. Secondly, the effect of the organic solvent on the catalyst activity and durability (a vital factor for the large scale industrial production) is also not considered in the LLE calculation only. Thirdly, since some of the binary interaction parameters were estimated by the UNIFAC (group contribution) method, the accuracy of LLE calculation

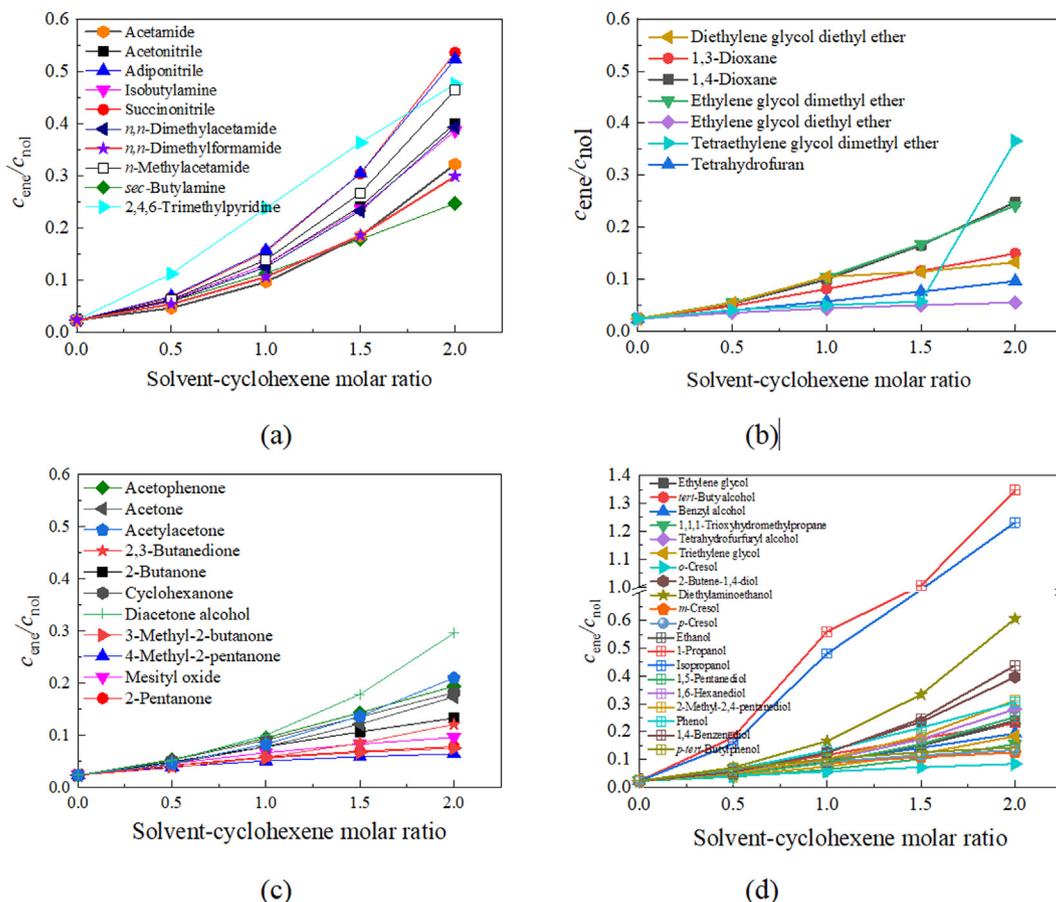


Fig. 2. Effect of solvent dosage on the value of m . (a) nitrides, (b) ethers, (c) ketones, (d) phenols + alcohol. Reaction condition: temperature = 393.15 K, pressure = 1.0 MPa, molar ratio of cyclohexene:water:cyclohexanol = 1:14:0.1.

results are not fully ensured when the solvent is added. Therefore, the solvents with high partition coefficient m should be taken as candidates for further experimental investigation and validation.

3.2. Yield investigation at the reactor scale

In order to evaluate the practicability of the solvents pre-selected by LLE calculation, one question must be answered at the reactor scale, namely whether these solvents could substantially improve the equilibrium conversion without causing any side reactions and deactivating the catalyst. For this purpose, the effect of these solvents on the product yield, product selectivity, and catalyst stability was experimentally investigated in a high-pressure batch tank reactor for the cyclohexene hydration. Table 1 shows how the cyclohexanol yield was affected by the preferred solvents. The GC analysis result showed that side reactions occurred after the addition of some solvents (e.g. *tert*-butanol, 2-butene-1,4-diol, ethylene glycol diethyl ether, and so on). From the perspective of atom economy, these solvents were excluded. The remaining solvents could be reclassified by their contribution to the yield of cyclohexanol. Some of the solvents contributed little to the improvement of cyclohexanol yield, or even reduced the yield drastically. Only the solvents *o*-methylphenol, benzyl alcohol, and acetophenone could significantly improve the cyclohexanol yield without causing the side reactions. The addition of these solvents leads to cyclohexanol yield increasing from 12.3 % to 22.3 %, 17.5 %, and 16.1 %, respectively. It is interesting to find that these three solvents are partly miscible with water (Brown et al., 2000;

Luo et al., 2015; Xin et al., 2016), suggesting that extracting cyclohexanol from the aqueous phase is more effective to dissolving cyclohexene into the aqueous phase to intensify the hydration reaction.

Then, attention was paid to whether the catalyst would be affected by the solvents. For this evaluation, the catalysts were repeatedly used under the same reaction conditions. According to reported studies, the cyclohexanol yield decreases after the catalysts are reused several times (Ishida, 1997; Zhang et al., 2002). It should be attributed to the fact that the active sites get partly covered by the polymers formed via the polymerization of a small amount of cyclohexene (Ishida, 1997; Zhang et al., 2002). In this case, the catalysts were not intrinsically damaged, and they could be reactivated after decomposing the polymers at high temperature. As shown in Fig. 3a, the yield reduced from 12.2 % to 8.1 % without the addition of solvent after the catalysts were used 6 times, and returned to ~ 12.0 % after the catalysts were calcined at high-temperature. This was consistent with the results reported in other works (Ishida, 1997), suggesting that the repetitive experiments were reliable. The effect of solvent on the catalyst stability is illustrated in Fig. 3b-d. The cyclohexanol yields were almost the same for the fresh and reactivated catalysts, although they reduced after the repeated use of catalyst. Therefore, the solvents *o*-methylphenol, benzyl alcohol, and acetophenone do not have a negative effect on the catalyst. These three solvents can improve the cyclohexanol yield more than the ones recommended in previous literature (Panneman and Beenackers, 1992a, b, c, d; Qiu et al., 2013; Shan et al., 2011a, 2011b). The primary reason for finding

Table 1
Effect of different solvents on the cyclohexanol yield.

Solvent		Yield (%)	Solvent		Yield (%)	
Blank Nitride	No-solvent	12.30	Ether	Diethylene glycol dimethyl ether*	8.35	
	Acetamide*	3.67		1,3-Dioxane	12.44	
	Acetonitrile	2.54		1,4-Dioxane	12.84	
	Adiponitrile	5.66		Ethylene glycol dimethyl ether*	14.64	
	Isobutylamine	0.00		Ethylene glycol diethyl ether*	10.87	
	<i>n,n</i> -Dimethylacetamide	0.13		Tetraethylene glycol dimethyl ether*	8.26	
	<i>n,n</i> -Dimethylformamide	0.12		Tetrahydrofuran*	10.06	
	<i>n</i> -Methylacetamide	0.51		Phenol and alcohol	1,4-Benzenediol	14.64
	<i>sec</i> -Butylamine	0.00			Benzyl alcohol	17.37
	Succinonitrile	1.48			2-Butene-1,4-diol*	2.53
	Ketone	2,4,6-Trimethylpyridine	13.22	Diethylaminoethanol	0.00	
		Acetophenone	Acetophenone	15.60	Ethanol*	8.9
			Acetone*	9.61	Ethylene glycol*	11.88
Acetylacetone*			13.55	1,5-Pentanediol*	11.76	
2,3-Butanedione*			13.23	1,6-Hexanediol*	10.99	
2-Butanone			13.57	Isopropanol*	8.96	
Cyclohexanone			12.69	<i>o</i> -Methylphenol	21.91	
Diacetone alcohol*			15.19	1-Propanol*	9.12	
3-Methyl-2-butanone			12.95	<i>p-tert</i> -Butylphenol	14.65	
4-Methyl-2-pentanone			11.86	<i>tert</i> -Butanol*	11.57	
Mesityl oxide*	14.60		Tetrahydrofuryl alcohol*	11.22		
2-Pentanone	12.41	Triethylene glycol*	8.49			
			1,1,1-Trioxyhydromethylpropane*	10.46		

Reaction condition: temperature = 393.15 K, pressure = 1.0 MPa, molar ratio of cyclohexene:water:solvent = 1:14:0.2, catalyst mass fraction = 20 %, time = 2 h. *: side-products were determined with using this solvent.

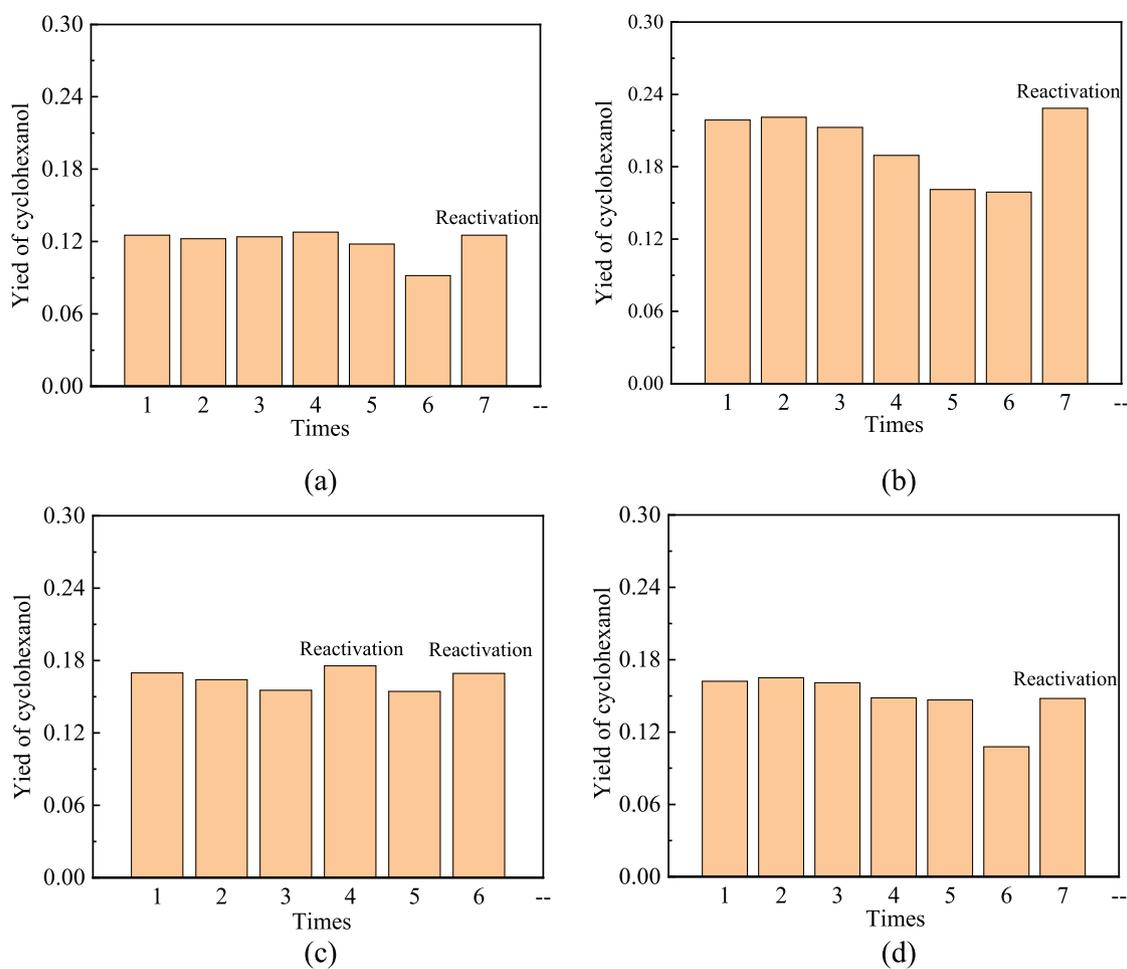


Fig. 3. Reuse of catalyst in different solvents. (a) no solvent, (b) *o*-methylphenol, (c) benzyl alcohol, and (d) acetophenone. Reaction condition: stirring rate = 1200 rpm ($N_p \approx 4.86$), temperature = 393.15 K, pressure = 1.0 MPa, molar ratio of cyclohexene:water:solvent = 1:14:0.2, catalyst mass fraction = 20 %, time = 2 h.

them in this work was the introduction of the parameter m , which helped to pick out rapidly the potential solvent candidates from a great deal of organic compounds.

3.3. Process evaluation at the system scale

Fig. 4a shows the most successful industrial process technology for cyclohexene hydration, developed by Asahi Chemicals in 1980 s

(Ishida, 1997; Masahiro and Fukuoka, 1987). The reactants (cyclohexene and water) are continuously pumped into a continuous stirred tank reactor (CSTR), in which the reaction occurs until the chemical equilibrium is almost reached. Then, the reaction mixture is cooled in a heat exchanger, and then sent to a decanter for liquid–liquid phase separation. The organic phase (mostly unreacted cyclohexene and cyclohexanol product) is separated in a distillation column. The unreacted cyclohexene is collected as top distil-

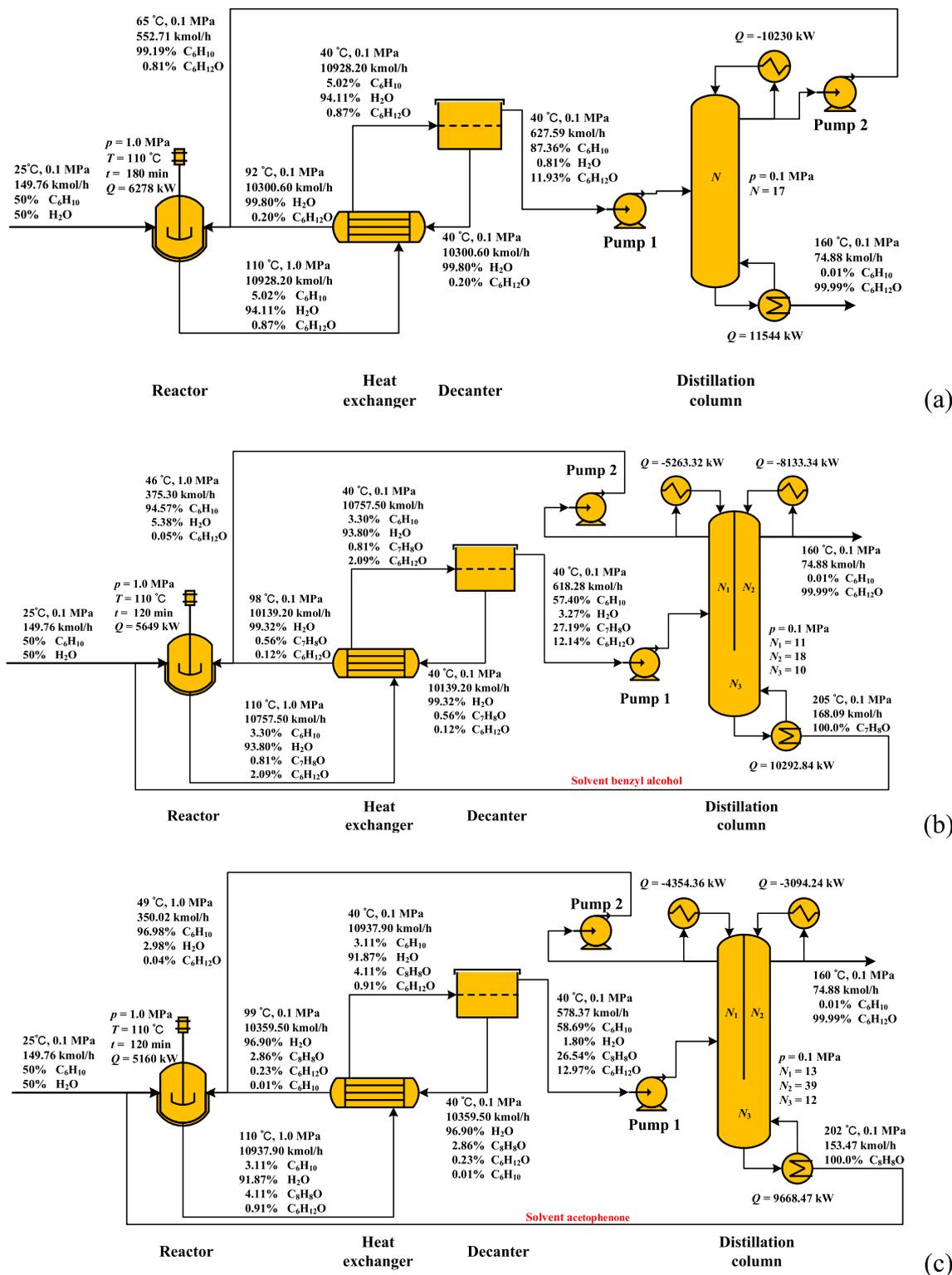


Fig. 4. Technological process of cyclohexene hydration. (a) Developed by the Asahi Chemicals Co. Ltd. Company without using solvent, (b) developed in this work using benzyl alcohol as solvent, and (c) developed in this work using acetophenone as solvent.

late and recycled back to the CSTR, while the cyclohexanol product is obtained as bottom product. The aqueous phase (mainly containing excess water and catalyst) is recycled to the CSTR through the feed effluent heat exchanger, being heated by the reaction mixture outlet from the reactor.

After adding solvent, an effective liquid–liquid dispersion is still necessary to achieve a satisfactory reaction rate, even though the solvent could drastically improve the solubility of cyclohexene in water. As a result, a CSTR is still the best choice for the solvent-assisted cyclohexene hydration reaction. A liquid–liquid decanter is also required to separate the reaction mixer from the CSTR. The aqueous phase (containing mostly water, solvent, and catalyst) is recycled to the CSTR. The organic phase (mostly cyclohexene, cyclohexanol, and solvent) has to be further separated. Due to the introduction of solvent into the organic phase, the separation sequence should be modified based on the conventional process. Table S8 shows that the chemicals in the organic phase have large differences in the boiling points, thus distillation is a suitable method for their separation. The specific separation scheme is defined after the thermodynamic analysis.

3.4. Thermodynamic analysis

Table S9 provides the azeotropic data from literature and the calculated ones based on the NRTL model in Aspen Plus. The relative error is less than 5 %, indicating that it is adequate to use the NRTL model and the parameters listed in Table S2 for the simulation of distillation. Table S10 lists the NRTL model interaction parameters related to the solvents selected. The VLE data calculated based on the parameters in Table S10 are shown in Fig. 5.

In order to verify the reliability of data, VLE experiments were conducted for these systems. Fig. 5 shows the comparison between experimental and calculated data. These values are relatively close for the solvent–cyclohexene systems, with the average deviation of 2.2 % (as shown in Fig. 5a–c), which proves that the interaction parameters provided in Table S10 are reliable for the solvent–cyclohexene systems. Fig. 5d–f compares the experimental and predicted values of the VLE for the solvent–cyclohexanol systems. Fig. 5d shows that these values for the benzyl alcohol–cyclohexanol system are relatively close, with an average deviation of 2.7 %, confirming that their binary interaction parameters are reliable. Fig. 5e implies that there was a large deviation between the experimental and predicted values for the acetophenone–cyclohexanol system. For this reason, the experimental data of this system were used to correlate the NRTL interaction parameters (which are listed in Table S10). The VLE data predicted based on the new parameters (also shown in Fig. 5e) has an improved average deviation of about 2.9 %, indicating that the new parameters are reliable.

Fig. 5f indicates that the binary interaction parameters provided by Aspen Plus are not reliable for the *o*-methylphenol–cyclohexanol system. The experimental data also suggests that when x_B increases to 1, the VLE lines are very close, which would make the separation difficult, the process more complex and the total cost much higher. That is, from the system scale perspective, *o*-methylphenol is not a good candidate, although it performs best at the reactor scale. We have made a great effort to correlate the experimental data in Fig. 5f to obtain relevant NRTL parameters. However, due to the thermodynamic complexity (azeotropy appears at fairly high concentration of *o*-methylphenol), the data correlation did not converge properly. For the purpose of correlating the NRTL parameters for this complex system, more experimental data should be provided and a more robust algorithm should be developed accordingly (outside the scope of this paper).

For these reasons, the separation process is designed only for benzyl alcohol and acetophenone. Considering the large tempera-

ture difference between the separated components, a dividing-wall column (with a top wall configuration, and an insulated dividing-wall) is proposed, as illustrated in Fig. 4b–c. The unreacted cyclohexene and cyclohexanol product are withdrawn from the top left and top right sides of the column, respectively, while the inert solvent is collected as bottom product. Cyclohexene and the solvent are then recycled to the CSTR.

3.5. Reaction kinetics determination

Reaction kinetics is indispensable for the reactor design. In order to collect accurate data of intrinsic kinetics, the interior and external mass transfer resistance must be eliminated. The size of the HZSM-5 catalyst particles is so small (30–50 nm) that the interior mass transfer resistance can be always ignored (Shan et al., 2011a, 2011b; Zhang et al., 2002). The external mass transfer resistance could be eliminated by increasing the stirring rate. Fig. 6 illustrates the effect of the stirring rate on the cyclohexanol yield. When the stirring rate changes from 400 rpm to 1200 rpm, the cyclohexanol yield significantly increases, suggesting that the external mass transfer resistance has been reduced. After the stirring rate was increased from 1200 rpm to 1600 rpm, the cyclohexanol yield barely changed, which indicates that the external mass transfer resistance can be considered eliminated at 1200 rpm with the power number $N_p \approx 4.86$. In the subsequent experiments, the kinetics was determined at 1200 rpm.

The reaction kinetics was first investigated without the addition of solvent, as shown in Fig. 7. The reaction rate increases with the increase of temperature, water–cyclohexene molar ratio, and catalyst concentration. The equilibrium conversion decreases with the increase of temperature, suggesting that the cyclohexene hydration is an exothermic reaction. The effect of the solvents benzyl alcohol and acetophenone on the reaction kinetics is shown in Fig. 8 and Fig. 9, respectively. Several common conclusions could be drawn from these kinetic data. The increase in cyclohexene–solvent molar ratio results in the acceleration of the reaction rate and the improvement of the equilibrium conversion. When the molar ratio of cyclohexene to solvent increased from 1:0 to 1:1, the cyclohexanol yield increased from 12.3 % to 34.8 % (as shown in Fig. 8a) and to 27.6 % (as shown in Fig. 9a) for benzyl alcohol and acetophenone, respectively. This should be attributed to the ability of these solvents to draw the cyclohexene into the aqueous phase and keep the cyclohexanol in the organic phase. Raising the temperature leads to an increase of the reaction rate, but it is detrimental to the equilibrium conversion as the cyclohexene hydration is an exothermic reaction (Ishida, 1997). This did not change after the addition of solvent. The molar ratio of water–cyclohexene had a minor effect on the reaction rate and equilibrium yield, as the cyclohexene hydration occurs in the aqueous phase. Cyclohexene and cyclohexanol concentrations in the aqueous phase change slightly with the variation of the molar ratio water–cyclohexene. Increasing the catalyst concentration could accelerate the reaction, due to the increase of the amount of active sites. For the solvents investigated, the cyclohexanol yield no longer increased after the catalyst mass fraction exceeded 20 %, implying that the catalyst mass fraction should be kept below 20 %.

The dependence of cyclohexanol yield on the reaction temperature, cyclohexene–water molar ratio, solvent–cyclohexene molar ratio, and catalyst concentration is described by a power law type of equation:

$$Y = aT^b MCW^c w_{cat}^d t^e MSC^f \quad (5)$$

where T is the reaction temperature (°C), MCW is the molar ratio of cyclohexene–water, w_{cat} is the ratio of catalyst weight to the total mass, MCS is the molar ratio of solvent–cyclohexene,

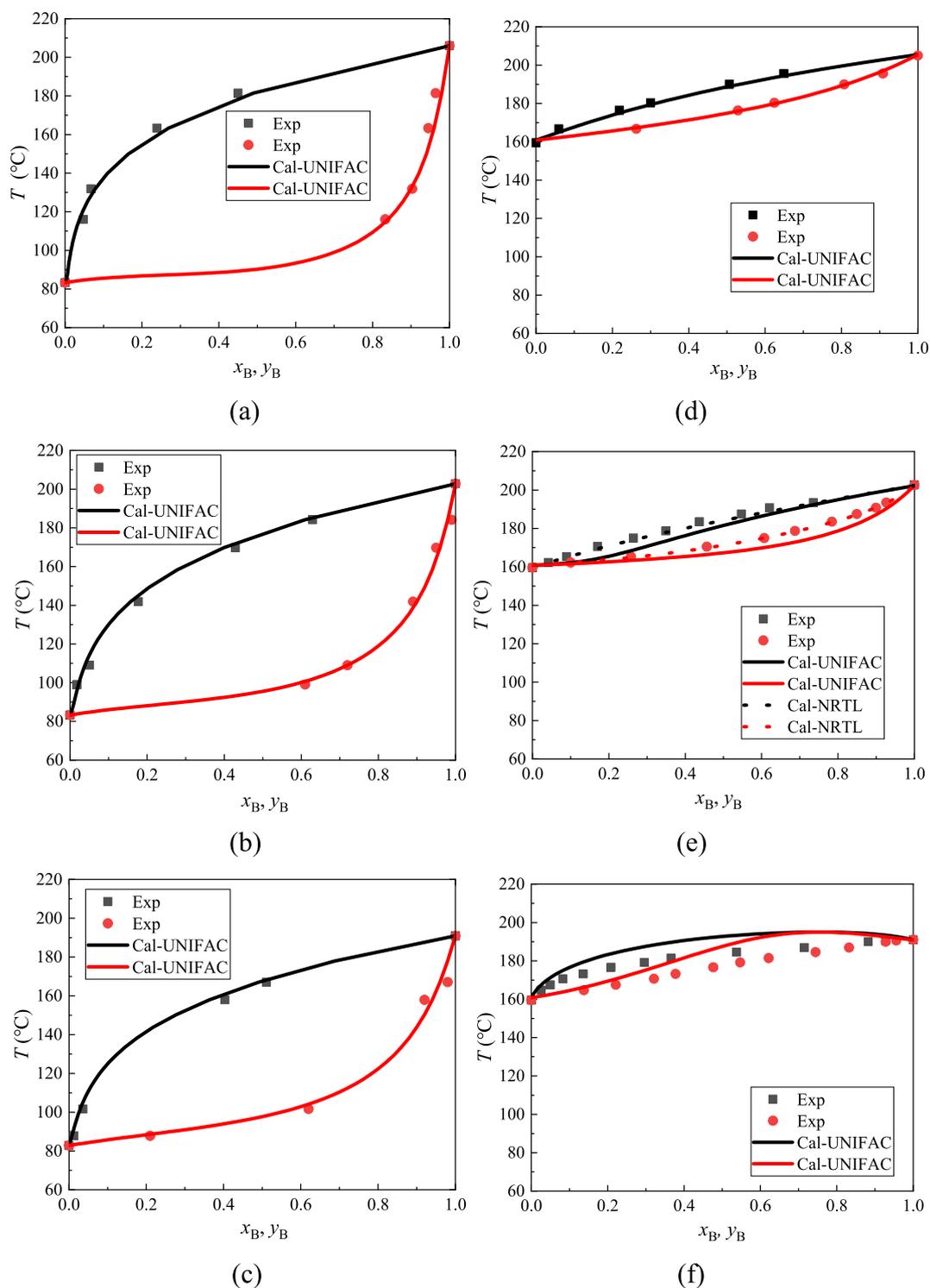


Fig. 5. Vapor-liquid phase equilibria verification. (a) Cyclohexene-benzyl alcohol, (b) cyclohexene-acetophenone, (c) cyclohexene-*o*-methylphenol, (d) cyclohexanol-benzyl alcohol, (e) cyclohexanol-acetophenone, (f) cyclohexanol-*o*-methylphenol.

and t is the reaction time (min). The parameters a , b , c , d , e , and f were correlated with the experimental data and listed in Table 2 for different solvents. The average correlation deviation was less than 10 %. Based on this equation, the reactor for the hydration of cyclohexene was simulated using the RStoic model in Aspen Plus.

3.6. Process evaluation and optimization

To make a fair comparison of the processes shown in Fig. 4, the operating conditions were optimized to minimize TAC. The optimization process is shown in Figure S4. Based on the design specifications listed in Table S13, the effect of reaction time, reaction

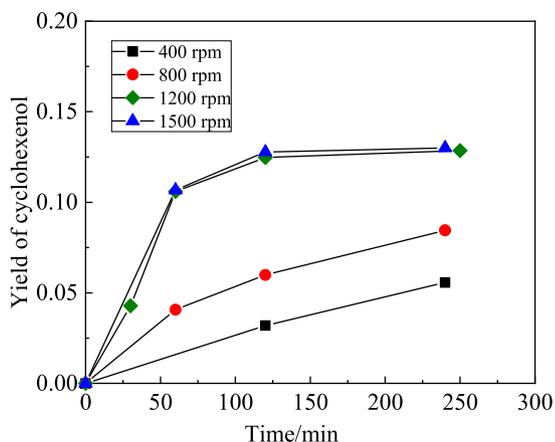


Fig. 6. Effect of the stirring rate on the cyclohexene hydration. Reaction condition: temperature = 393.15 K, pressure = 1.0 MPa, molar ratio of cyclohexene: water = 1:14, catalyst mass fraction = 20 %.

temperature, catalyst concentration, and molar ratio of solvent to cyclohexene on TAC was systematically investigated for all the processes (as shown in Figures S5-S7 in the Supporting Information). The low limit of the investigated temperature was 110 °C, since a lower temperature would lead to a much lower catalytic activity (Shan et al., 2011a, 2011b; Zhang et al., 2002).

3.7. Process comparison and economic analysis

It can be observed in Figure S5 that the minimum TAC of the process without solvent was obtained at a reactor temperature of 110 °C and reaction time of 180 min. Figure S6 shows that the minimum TAC of the process with benzyl alcohol as solvent is obtained at a reactor temperature of 110 °C, reaction time of 120 min, and solvent-cyclohexene molar ratio of 0.3. Figure S7 shows that the minimum TAC of the process with acetyl benzene as solvent was obtained at a reactor temperature of 110 °C, reaction time of 120 min, and solvent-cyclohexene molar ratio of 0.7. At these optimized operation conditions, the corresponding information is shown in Fig. 4 for each stream and equipment. Table 3 provides the equipment and operation cost of each equipment for different processes. In case of the conventional process without using solvent, the total cost of the reactor and distillation column are \$ 3.38 m (with equipment cost of \$ 1.90 m and operation cost of \$ 1.48 m) and \$ 3.35 m (with equipment cost of \$ 0.513 m and operation cost of \$ 2.84 m), respectively. They were very close and altogether accounted for 94 % of the TAC of the whole process. The solvent could reduce the total cost of the reactor by accelerating the reaction but increases the total cost of the distillation column for recovering the solvent. As a result, the close total cost suggests that the solvent effect on the synthesis and separation sections should be considered simultaneously. The operation cost of the distillation column is nearly 85 % of its total cost. Such a large proportion indicates that it is a sensible method to use a dividing-wall

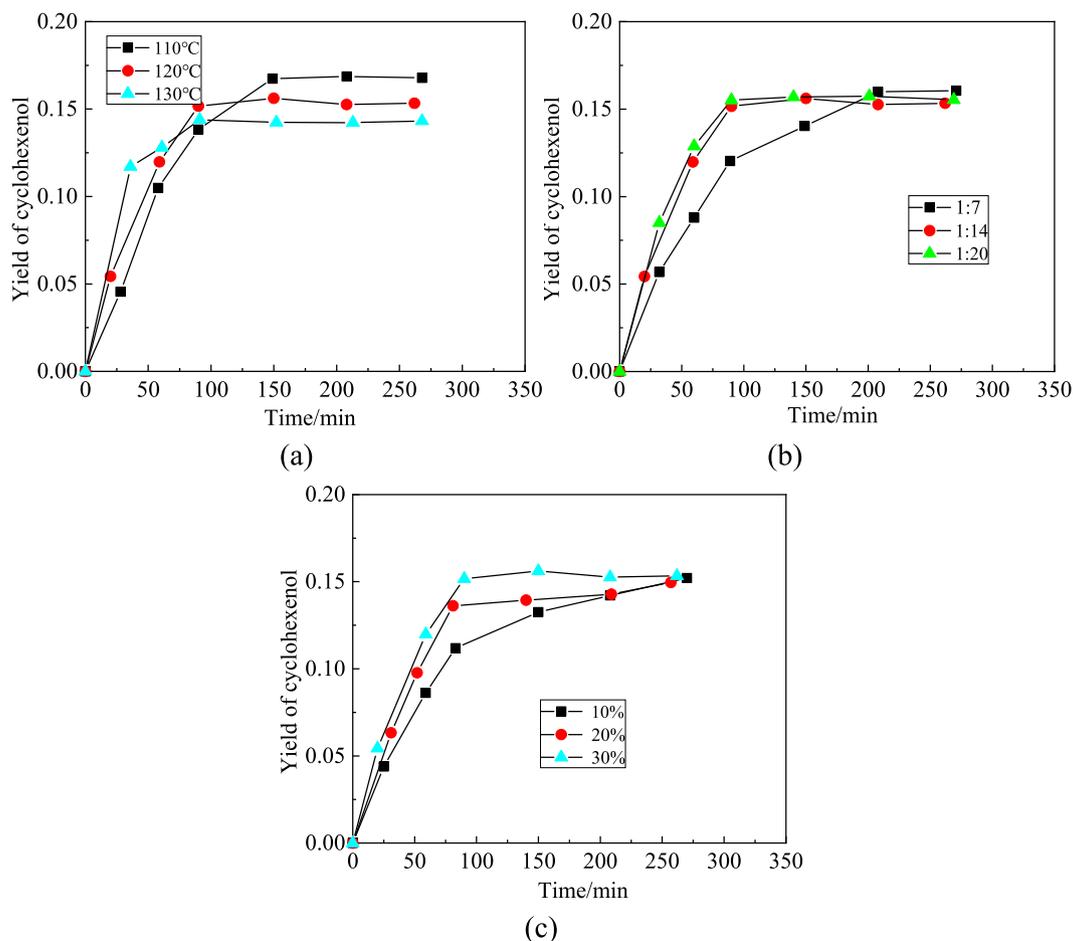


Fig. 7. Reaction kinetics of cyclohexene hydration without solvent. (a) Effect of reaction temperature. (b) Effect of cyclohexene-water molar ratio. (c) Effect of catalyst concentration. Reaction condition: temperature = 393.15 K, molar ratio of cyclohexene:water = 1:14, stirring rate = 1200 rpm ($N_p \approx 4.86$), pressure = 1.0 MPa, catalyst mass fraction = 20 %.

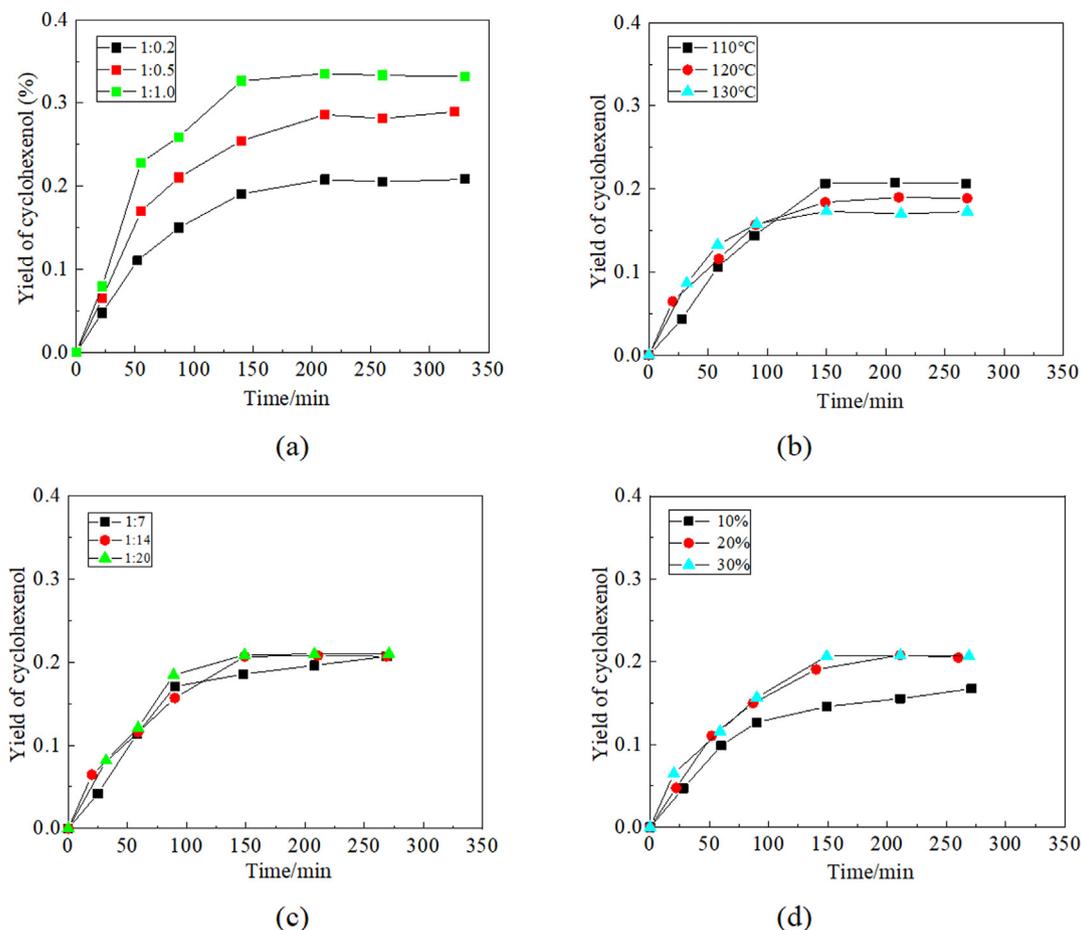


Fig. 8. Reaction kinetics of cyclohexene hydration in the solvent of benzyl alcohol. (a) Effect of cyclohexene-solvent molar ratio. (b) Effect of reaction temperature. (c) Effect of cyclohexene-water molar ratio. (d) Effect of catalyst concentration. Reaction condition: temperature = 393.15 K, molar ratio of cyclohexene:water:solvent = 1:14:0.2, stirring rate = 1200 rpm ($N_p \approx 4.86$), pressure = 1.0 MPa, catalyst mass fraction = 20 %.

column to intensify the separation section for the solvent-assisted process. Using solvents benzyl alcohol and acetophenone in the process, the TAC reduces from \$ 7.16 m to \$ 6.59 m by nearly 8 %. Such a reduction could bring considerable absolute savings in the total annual cost, since billions of kilograms of cyclohexanol are produced annually in the world (Musser, 2011).

Although the two solvent-assisted processes had similar TAC values, the solvents benzyl alcohol and acetophenone intensified the processes in different ways, as listed in Table 3. The TEC/3 of the whole process decreased from \$ 2.84 m to \$ 2.27 m (by 21 %) when benzyl alcohol is used as solvent, while the TOC was almost unchanged. The decrease of TEC should be attributed to the significant reduction of the reactor cost. Using acetophenone as solvent, the TEC/3 decreased from \$ 2.84 m to \$ 2.55 m (by 9 %), while the TOC from reduced from \$ 4.32 m to \$ 4.04 m (by 6 %). This means that the acetophenone solvent simultaneously reduced both TEC and TOC. The cost of the heating by steam (the main responsible for the CO₂ emissions) accounted for 95 % of the TOC. As a result, a higher TOC means more CO₂ emission. As shown in Table 3, the CO₂ emission and energy intensity reduced from 0.696 to 0.647 kg/kg, and from 4.937 to 4.638 MJ/kg, when replacing benzyl alcohol with acetophenone as solvent. From a sustainable development viewpoint, acetophenone is a better choice than benzyl alcohol. In comparison with the conventional Asahi process, the proposed process using acetophenone could reduce the CO₂ emission and energy intensity by 17 % and 16 %, respectively. Therefore, by using the multi-scale method proposed here, acetophenone is

chosen (out of ~ 100 organic solvents) as most suitable solvent for the cyclohexene hydration process. Although the energy usage is reduced by ~ 16 %, considering the large annual production of cyclohexanol worldwide, such a reduction is significant when translated to absolute values. Notably, the cyclohexanone market registered a demand of 6400 thousand tonnes in 2020 and is anticipated to grow at a healthy CAGR of 4.1 % in the span of the next ten years (ChemAnalyst, 2022).

The literature search confirms that acetophenone is being used as solvent for the cyclohexene hydration for the first time. Note that other studies reported the use of similar inert solvents for the cyclohexene hydration, such as sulfolane, ethylene glycol, and dioxane (Panneman and Beenackers, 1992b,c,d; Qiu et al., 2013; Shan et al., 2011a, 2011b), but they were all excluded in this work. Sulfolane is basically excluded in the first step due to its low value of the partition coefficient (m). Even if selected as a candidate, it would be eliminated in the following steps. The first reason is that its addition will decrease the equilibrium conversion, although it could accelerate the reaction rate (Panneman and Beenackers, 1992b,c,d). The second reason is that its boiling point (~285 °C at 101.3 kPa) is much higher than that of other candidates (*o*-methylphenol, benzyl alcohol, and acetophenone), which would make its separation and recovery more expensive. Additionally, sulfolane is a *tetramethylene sulfone*, so it was also excluded from an eco-friendly viewpoint. Ethylene glycol is excluded in the second step for two reasons. The first reason is that it shows poorer ability in improving the conversion, in comparison with other can-

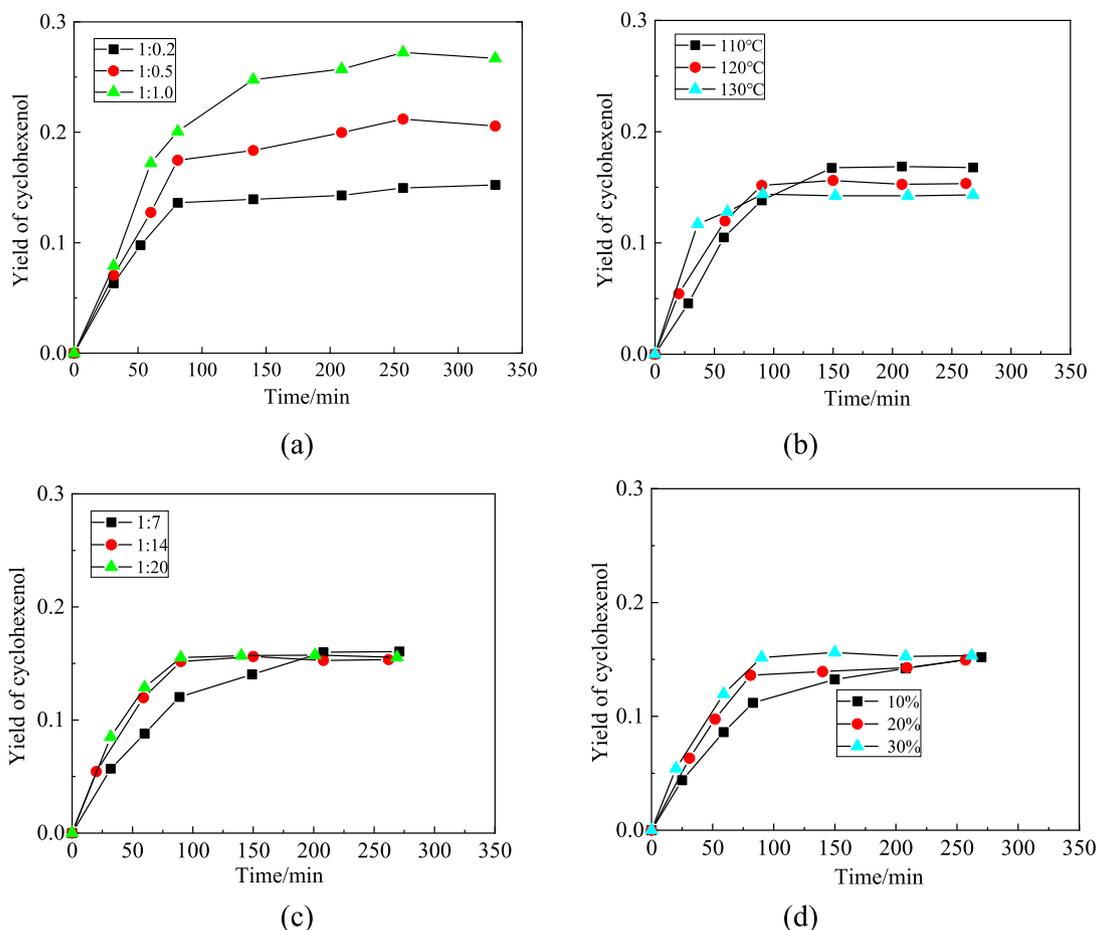


Fig. 9. Reaction kinetics of cyclohexene hydration in the solvent of acetophenone. (a) Effect of cyclohexene-solvent molar ratio. (b) Effect of reaction temperature. (c) Effect of cyclohexene-water molar ratio. (d) Effect of catalyst concentration. Reaction condition: temperature = 393.15 K, molar ratio of cyclohexene:water:solvent = 1:14:0.2, catalyst mass fraction = 20 %, stirring rate = 1200 rpm ($N_p \approx 4.86$), pressure = 1.0 MPa.

Table 2

Reaction rate constants for different solvents.

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>
Without solvent	0.3744	-0.6000	0.0479	0.1954	0.3603	0.000
Benzyl alcohol	0.0552	-0.0051	0.0110	0.1529	0.3775	0.3473
Acetophenone	0.1141	-0.1932	0.1124	0.1581	0.3094	0.3100

Note: the application range of these parameters were $110\text{ }^\circ\text{C} < T < 140\text{ }^\circ\text{C}$, $7 < MCW < 20$, $0.1 < w_{cat} < 0.3$, $0.1 < MSC < 1$.

Table 3

Cost distribution for different solvents^b.

Solvent		None	Benzyl alcohol	Acetophenone
Equipment cost/3 (\$/year)	Reactor	1.90×10^6	1.26×10^6	1.45×10^6
	Heat exchanger	4.13×10^5	4.41×10^5	3.93×10^5
	Decanter	1.19×10^4	1.19×10^4	1.39×10^4
	Distillation column ^a	5.13×10^5	5.53×10^5	6.97×10^5
TEC/3 (\$/year)	-	2.84×10^6	2.27×10^6	2.55×10^6
Operation cost (\$/year)	Reactor	1.48×10^6	1.32×10^6	1.21×10^6
	Distillation column ^a	2.84×10^6	3.01×10^6	2.83×10^6
TOC (\$/year)	-	4.32×10^6	4.33×10^6	4.04×10^6
TAC (\$/year)	-	7.16×10^6	6.60×10^6	6.59×10^6
Cost per kg product (\$/kg)	-	0.119	0.11	0.109
CO ₂ emission (kg/kg)	-	0.778	0.696	0.647
Energy intensity (MJ/kg)	-	5.538	4.937	4.638

^a The cost of the reboiler and condenser of the distillation column was included.

^b The cyclohexanol production was 60 ktpy = 7500 kg/hr (for 8000 hr/year).

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